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Modular Design of Full Body Exoskeleton suit for Industry, Construction and Military Purpose

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Abstract: ***Exoskeleton suits can be considered as a wearable robotic item ,where the main inution is to increase,improve& boost the physical performance of operator/user by a desired margin , it has a great practicality in the present time as it can be implemented in a variety of filed extending from Health sector to industries .The scope of this is to design a full-body,rigid,Active,performance type mobile-exoskeleton prototype, by targeting it as mainly applicable for the Industry sector , Defence sector& Civil-(construction,fire & safety department, etc) Sectors , which has seen to be taking a leap in to this genre .This paper explicates the methodology for the design which was modeled in "Solidworks" and analysys of mechanical strucuture– performed by "Ansys Workbench"& selection of actuation mechanism with a coustomised design which was validated by a series of analysis in "Altiar Flux Motor" , this paper also scrutinize very succinctly the "gait" cycle & its phases ,itsummarise the necessity of the "gait" analysis- which was performed by "Opensim"from which data was acquired for the analysis of designed prototype& for the guidance inactuation of the prototype by prediction & restriction of drive controller valueto the normal gait values during locomotion by "gait assist function",where the actuator control is primarly by the sensing of a series of "Strain guage" belts attached to the users muscles , 4 different control drivers used for actuation out of which for thigh joint the control drive was coustamised , the battery houses 728 high-performance Lithium-ion cells 0f "Panasonic-NCR18650B 3400MAh",for cooling system a common aluminium heat sink was used.the other critical factors which was considered during the designing was cost-effectiveness, minimal maintenance, ergonomic , efficiency and safety of the designed prototype is also pithily considered . the total weight of the designed prototype model was 79Kg & was able to lift & locomote at 1.36m/s with apayload of 258kg.***

Keywords: ***Exo-Skeleton Suit, Human-Gait Cycle, Human-Machine Interface, Robotics,Exosuit, Robotic actuator, Powered suit, Hardsuit, Exoframe.***

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I. INTRODUCTION

The exoskeleton is a suit that assists the wearer by boosting their strength and endurance.

It also gives the wearer superhuman powers. So, it is perfect candidate for Industry, military and rescue fields. Idea is to design and simulate an electric-powered full-body exoskeleton suit with aim of long battery life, Better controls, weightlifting capacity of up to300 kg& total weight under 60 Kg. In general, manufacturing industries with 30-250kg subassemblies typically use hanger mechanism, cranes, robots, semi-automatic lifters.

The initiative taken by the Robo-mate is one of the first propositions made to retain the exoskeleton notion to the production sectors for restricting the manufacuting industries only to Europe& to preserve the employment opportunities in europian countries[14]. For 13 out of 26 industrial exoskeletons, some evaluations of the physical load reductions were performed[15]. Exoskeletons are important machines to decrease the risk factors associated with Stressed work musculoskeletal injuries. At this point, however, several issues hinder acceptance in industrial applications. The main issue is human-machine interaction and implications for standardization[16]

According to a study, more than 72% of exoskeleton robots use an electric motor for actuation. Around 20% of exoskeleton robots are pneumatically powered. Hydraulic actuation was utilized by about 5% and about 3% use alternative or hybrid actuation methods[18]. Pneumatic Air Muscles (PAM) actuation is not feasible due to its Precision and control[8].

II. MECHANICAL DESIGN

The consideration taken in the mechanical design was to be simple, Lightweight, Mobile ,Safe, rigid, Ergonomic & the possibility to accomodate, to different operators,. The mingling factors between ergonomic principles and biomechanics of a average human was the crucial criteria that was to be considered. Most designs was found to use passive actuatuion but it was unable to give the weight support which was well needed in our case **[12]**. Other main feature considered was the design to be "anthromorphic" in nature, which according to authors of**[10]**&**[5].**faciliated the actuation or locomotion of the exskelton very well within the human jurisdiction.

The software's used: Solidworks 2020 was used to build the CAD of mechanical prototype , and Ansys V16.2 was used to simulate it under static

loads conditions and to extract stress component & and angular moment developed at the joints. and analysis when designing.

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Human gait data was acquired from the simulation performed on OpenSim.The suit has been developed to fit operator as per the dimensions from Table 1

Table I: 95th Percentile man measurements with max. and min. values

Indicator	Minimum	Maximum	Ideal
Operator weight	58 kg	80kg	68 kg
Height	160 cm	183 cm	170cm
Chest(flexible)	32 in	46 in	36 in
Waist	32 in	38 in	34 in
Foot size(UK)	8	9.75	9

A human model can be considered as the representation dimension & characteristics of human body with according ratio, it will help us to keep a reference to our designs, In Literature there we can see a number of models which can be taken as reference, here in our case we are taking the model from the study of Drillis and Contini **[22]** ,in which we estimate the dimension of human segments by taking reference to the height such that as show in table II

Table II Dimension refernce for design

Features	%Height
Hand	10.8
Shoulder to elbow	18.6
Elbow to wrist	14.6
Knee to hip	20.0
Knee to ground	28.5

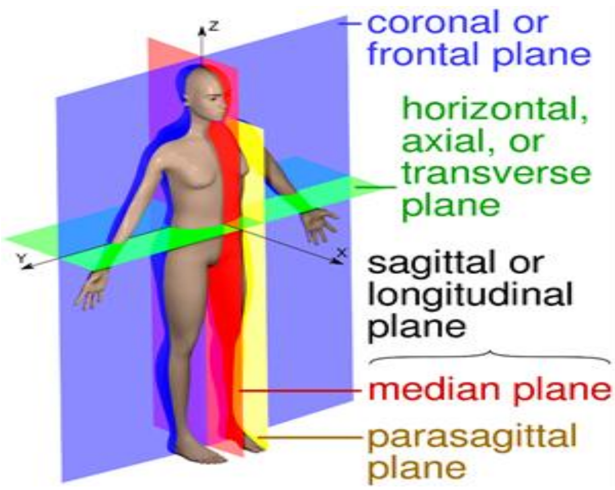

Fig. 1.Human Mannequin with planes.

From the Bio-Mechancs literature of a human locomotion we can observe that there are primarly 3 planes which are , a) the frontal or coronal plane, b) the horizontal axial or transverse plane & c) sagittal or longitudinal plane, by which the 3-dimensional human movements & gait can be represented & here the individual planes dissect the human body as given above , the most important plane here from which we can consider or acquire theangular moment , Load produced & relative motion for the joints & this plane segments is interpretedas longitudinal or saggital plane **[5]**. Bio-mechanically an human body has a total of around 24-DOF (Upper Body 10-DOF & Lower Body 14-DOF) Musculoskeletal Model while excluding the human head **[23]** it is to be noted that Generally, when the human body moves under flexion and extension knee and hip joints are active while, ankle joint acts as passive**[5]**, But it will very much convoluted to achieve, So in the final design the design with 7-DOF was selected, when by taking reference to preeding literature reviews the - bio-mechancis of a exoskeleton with 7-DOF(Upper Body 4-DOF & Lower Body 3-DOF) appeared sensible & here as the actuation of exoskeleton is full-active the movement or actuation is restricted by the drive-controller, Such that max-amount of range of actuation is given below – Table –I for Lower Body & Table –II for Upper body

Table III : Motion Range Values Lower Limb Body

Joint	Human Arm	Exoskeleton Arm
Shoulder	-120°to 90°	-50° to 40
Elbow	0° to 135°	0° to 120°
Wrist (rotation)	-90° to 90°	-80° to 80°

TableIV: Motion Range Values Upper Limb Body

Joint	Human Leg	Human Gait	Exoskeleton Leg
Hip	-65°to 120°	-17.5° to 25	-22° to 70
Knee	0° to 160°	-60° to 0°	-80° to 0°
Ankle	-50° to 20°	-14° to 11°	-16° to 18°

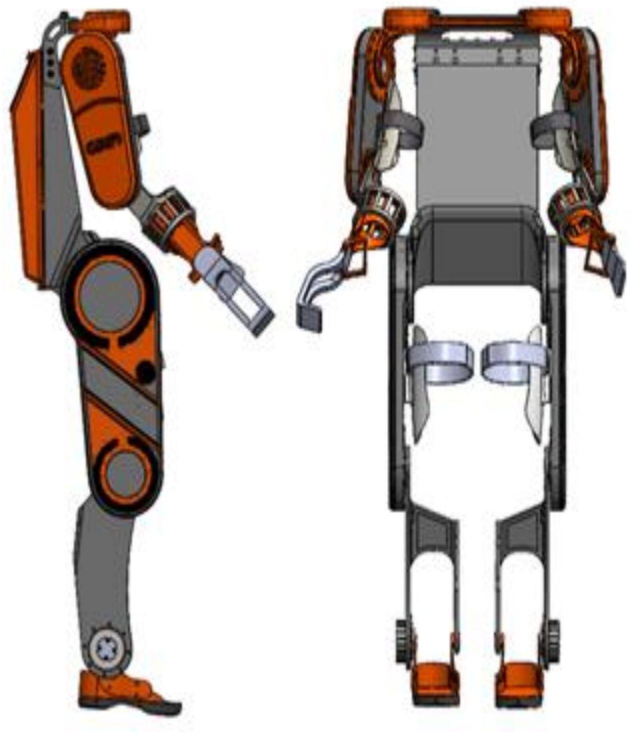

Fig. 2.Exoskeleton Isometric View

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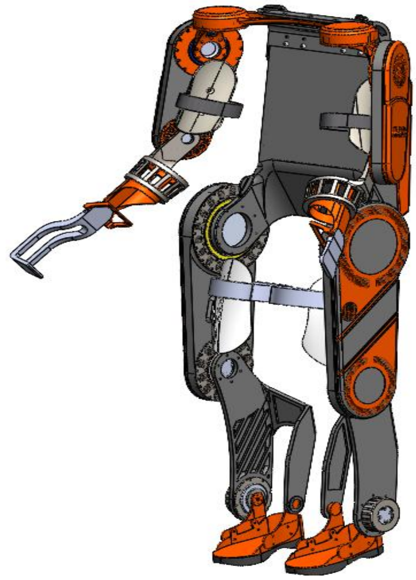

Fig.3.Exoskeleton side and Front view

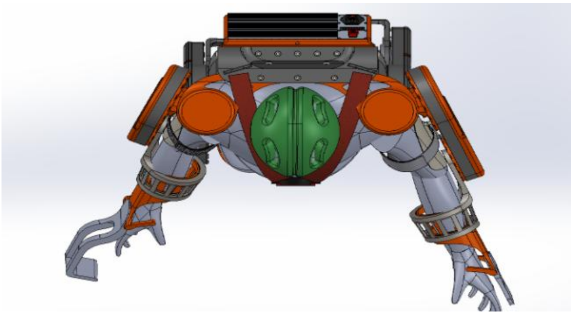

Fig. 4.Exoskeleton Top View

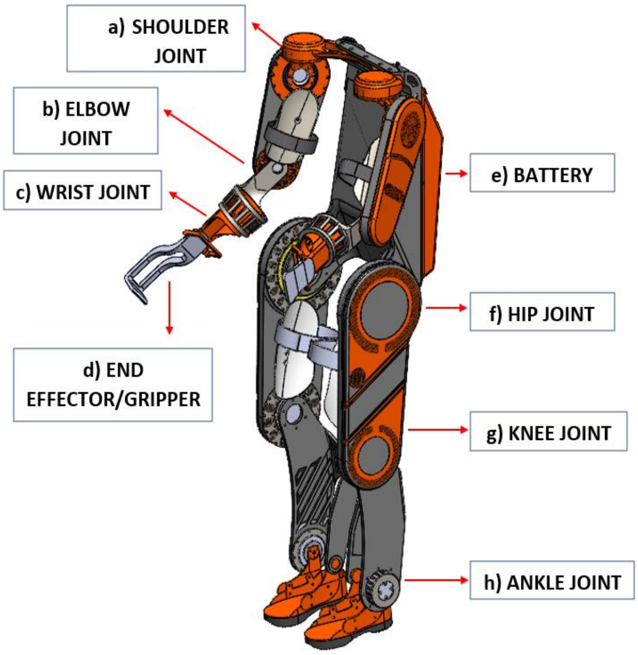

Fig. 5. Overall Structure of Exoskeleton Suit a) shoulder joint, b) elbow joint, c) wrist joint, d) end effector/ gripper, e) battery, f) hip joint, g) knee joint, h) ankle joint.

The muscle activity of the hip muscles/extensor is decreased. The exoskeleton suit creates uncomfortable stress in chest area. During static loading conditions of the forward-bended position, they observed similar reductions of back and leg muscle activity in the with-exoskeleton condition**[13]**. Hence we choose the suit's bending joint instead of the Spine Lumbar to Hip-Thigh joint.

Two variation of the gripper or end effector was designed, is shown in the above figures ,one on the left is the hook type which is the simple and quick solution for carrying an object or product as the hook type end effector will allow you to connect and disconnect the designated areas of the desired object very quickly with ease, the other variation which is on the right is designed such a way that it will act as support for operators/user when operating under low load conditions while using bare hands and fingers for the task , the overall design of end effector is such that it can be detached from the wrist joint so that it is possible for a series of variation of different desired end effector design to be used at different condition

III. HUMAN GAIT CYCLE ANALYSIS

The term gait cycle can be delineated as a series or a sequence of events in process of locomotion for a human which reccurent or persistent in a periodic manner which is showin below figure by a series of phases. The stance step (shown in the R: Stance, Fig. 6) and the swing phase (shown in the W: Swing, Fig. 6) of the human gait cycle are separated. The foot touches the ground during the stance process, the body's mass is stabilised, and the body is pushed forward during the latter stages of stance. As seen in Fig. 6, the stance step consists of five major events:

1. Heel-strike (HS)
2. Foot-flat (FF)
3. Midstance (MS)
4. Heel-off (HO)
5. Toe-off (TO)**[3]**.

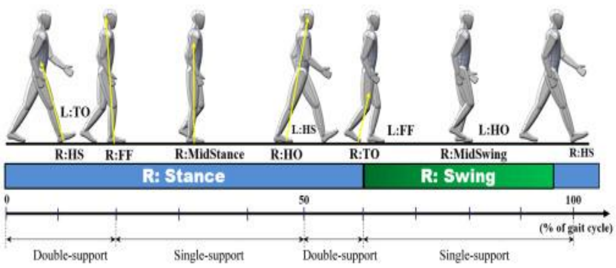

Fig. 6.Human Steps at different stage

i. *Heel-strike*: The first touch of one foot with the deck, also known as HS or foot-strike, represents the start of the gait .

ii. *Foot-flat*: The point at which the rest of the foot makes contact with the ground and the leg normally bears the entire weight of the body on one leg.

iii. *Midstance:* If the centre of mass is immediately above the ankle joint centre, it is called midstance. This is also the point at which the hip joint core is higher than the ankle joint.

iv. *Heel-off*: When the foot lifts off the ground in preparation for the body's forward momentum, something happens.

v. *Toe-off:* During the stance process, the last point of touch occurs.

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The events of a gait loop occur in strikingly identical cycles and are time-independent. As a result, the period is often represented in percentages rather than in terms of time. The initial HS is designated as 0%, and the corresponding HS of the same foot is designated as 100% (0–100%). The shoulder, knee, and ankle joints all have a range of motion during a typical gait period. Exoskeleton mechanism configuration is optimized by finding minimum work done during a single support phase of a gait cycle**[7]**.

A. The Model Obtained And Simulated In Opensim

Here the gait analysis was done by using the Opensim Gait model "Gait 2392"-which is a three-dimensional, 23-degree-of-freedom computer model of the human musculoskeletal system. (The models were created by Darryl Thelen (University of Wisconsin-Madison) and Ajay Seth, Frank C. Anderson, and Scott L. Delp (Stanford University)) From which the following plot for ankle-joint, Knee joint Hip joint & lumbar bending withrespect to the gait cycle percentage was obtained.

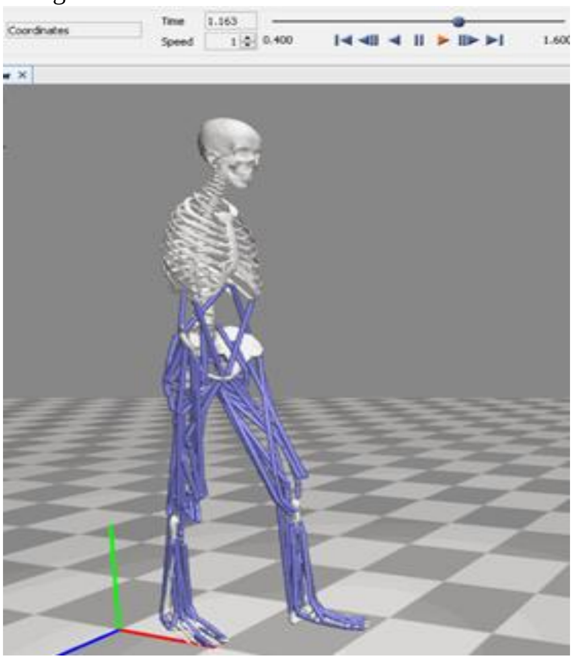

Fig. 7.The above picture shows the OpenSim Gait model "Gait 2392"

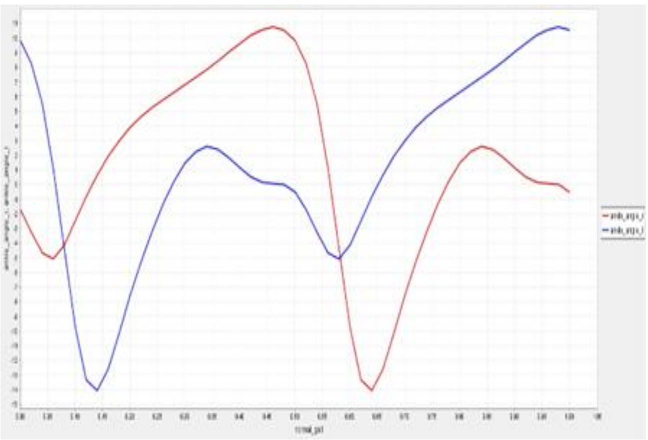

Fig. 8.Ankle graph (in degrees) w.r.t gait %

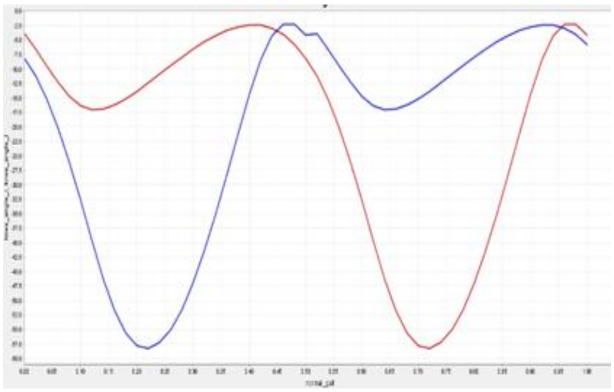

Fig. 9.Knee graph output (in degrees) w.r.t gait %

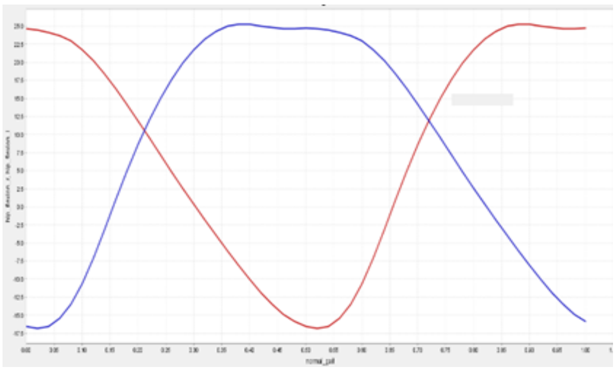

Fig. 10. Thigh angle (in degrees) w.r.t gait%

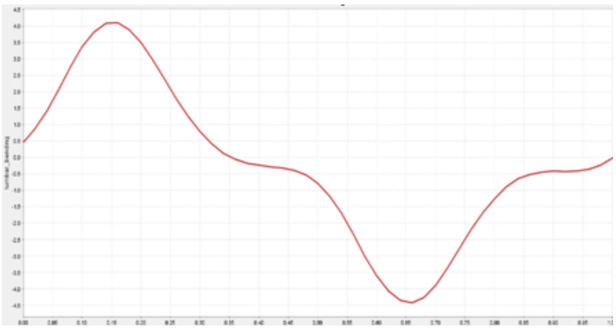

Fig. 11. Lumbar Bending w.r.t gait%

B. *Normal Ground Reaction Force*

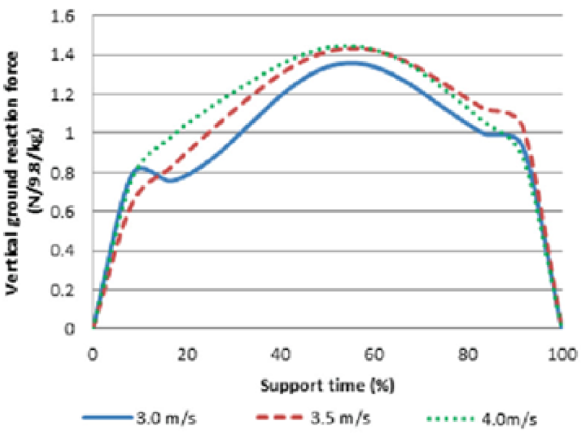

Fig. 12.Ground reaction force[4]

It was found with the reference "Dynamic Optimization of Human Running with Analytical Gradients"**[4]**for an average human moving with a speed of 3 m/s the reaction force at the foot was around 1.35 times of the body weight (can be seen in above graph Bodyweight% vs Gait %), here in this design also by taking similar intuition we can formulate the normal reaction for robotic exoskeleton suit.

So for 300kg payload , with consideration of desired exoskeleton bodyweight of 60Kg we will get the Max-normal ground reaction force as: 1.35 X 360 X 9.8 = **4700**Napprox.,the above graph can be inputd for torque calculation in Ansys W.r.t gait cycle

C. Torque and Analysis

The torque analysis was performed only for the lower body part by using the "Rigid Body dynamics tool" In "ANSYS-WORKBENCH". By taking input as the angular data and Normal reaction force data shown above. We were able to acquire the torque generated at the Main three joints in the lower body – (hip, knee& ankle) and the following observations were made.

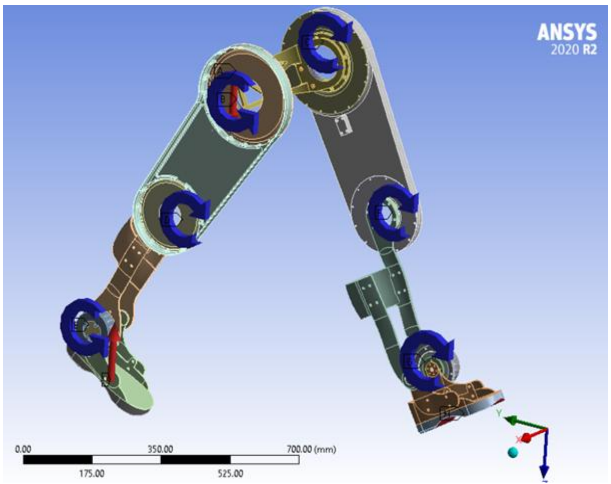

Fig.13 Illustration of Moment simulation on Ansys Work-Bench-Rigid-body dynmics

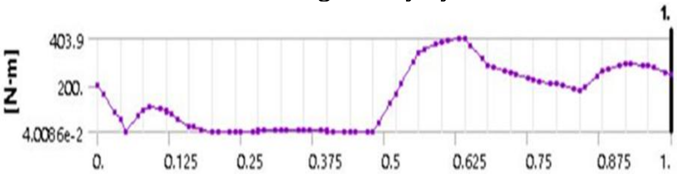

Fig. 14. Ankle Torque Analysis

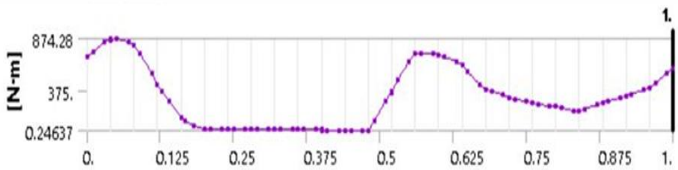

Fig. 15.Knee Torque Analysis

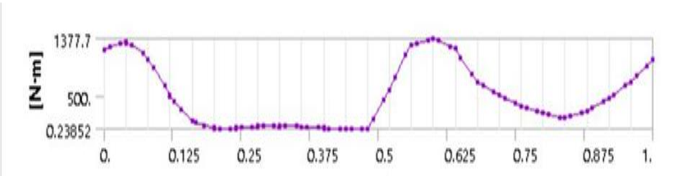

Fig. 16.Hip Torque Analysis

It was found that Max moment developed was **404**Nm,**875**Nm &**1377**Nm for Ankle,Knee&Hiprepectively.. It was found Similar to our study and simulation the tendancy of the exoskeleton to get the highest stess or pressure at the trunk or back which is then followed by thigh then shoulder. **[19]**..Gait assist function , From the gait data the degree of actuation during the locomotion in a normal gait can be predicted , this pre-eminence factor can be used as to reduce actuation lags**[9]**

This same notion cannot be used in the upper body as the event occurring in upper body Is not repeatable or dependentable any caertain locomotion phases.similar to gait cycle**[18].**

IV. STATIC STRUCTURAL ANALYSIS

The static structural analysis was performed on the exoskeleton suit to verify the structural strength of the different components used in the suit such as parts between elbow to shoulder, elbow to wrist, thigh, shoulder and back. The stress was evaluated by ANSYS software by considering various boundary conditions such as forces, torques and reaction forces from the motor and human gait analysis.

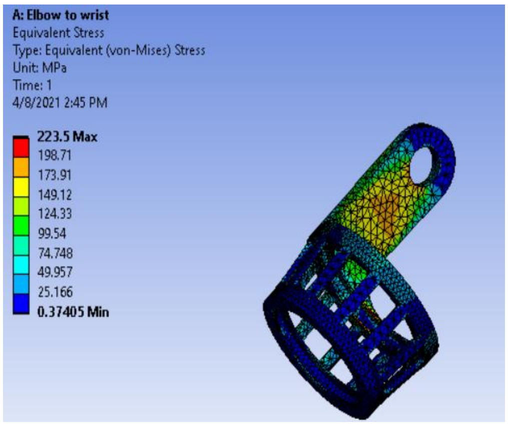

Fig. 17.Equivalent Stress of Elbow to Wrist part

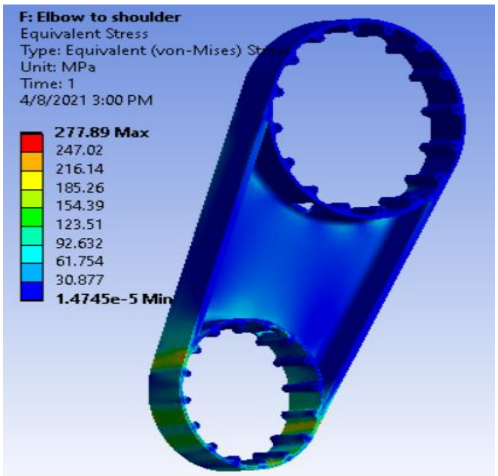

Fig. 18.Equivalent Stress of Elbow to Shoulder part

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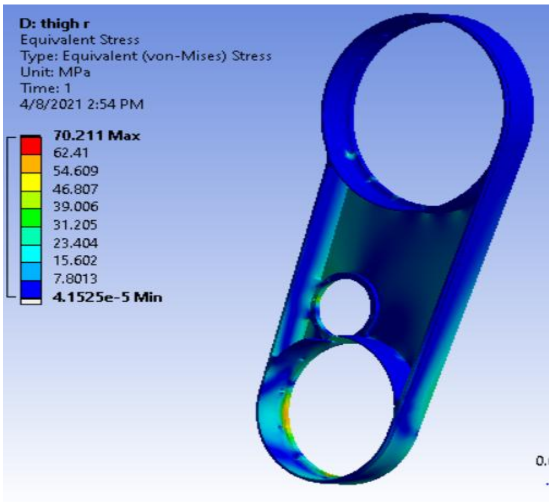

Fig. 19. Equivalent Stress of Thigh part

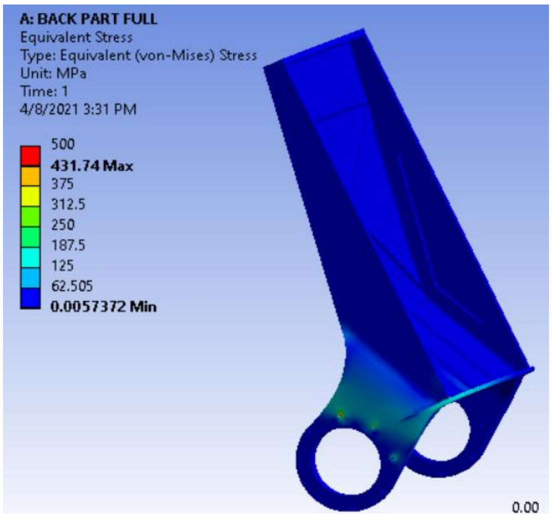

Fig. 20.Equivalent Stress of Back part

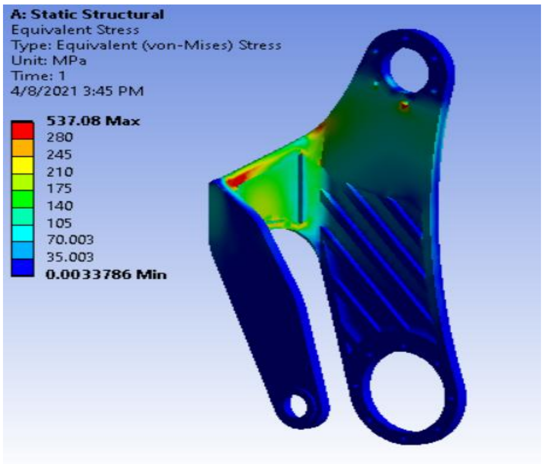

Fig. 21.Equivalent Stress of Knee to Ankle Part

V. BEARING SELECTION

Bearings are the most essential components for the movement of joints in our suit. To withstand 300Kg payload and also compact sizing, bearings of Light series 618xx/67xx bearings are integrated into Motor I/O mounts.

Table- V: Bearing Selection

Bearing	Dimensions	Static Load (kN)	Joint
6730	180*150*16	41	Thigh
6718	110*90*10	17	Knee
2x 61906	47*30*9	4.6	Ankle
61816	100*80*10	11.2	Shoulder
61810	65*50*7	6.8	Elbow
VB035CP0	105*90*8	7.97	Radius & Ulna

For Planetary Gearbox purpose bearings used are 6704, 6705, 6706, 6707, MR106zz, 61804, 61805, 61808.

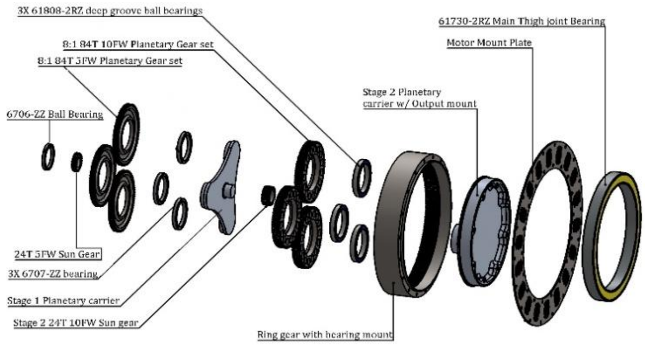

Fig. 22.Bearings in gearbox and Actuation joint

"Fig. 22" represents exploded view of actuator and almost all bearings of exoskeleton suit is housed in planetary gearbox and bigger bearings are only used in joints to counter radial and axial loads.

VI. MOTOR DESIGN

The design used flat high power density EC-motors combined with flat Harmonic Drive gearing. This allows a very compact electromechanical drive and are directly installed at each joint [17]. Harmonic drives are not suitable for high loads and are expensive, hence we use planetary gears inside motor's core to decrease its size. Reduction gears are mostly used when relatively high torques are required with small and lightweight motors. However, its demerits are: achievable speeds are reduced, and output friction and inertia are greatly amplified. The result is very small control bandwidth, which limits performance during dynamic tasks. Force and torque sensors only partially mitigate the above restrictions, as they increase weight, cost and complexity. Hence the motivation to research sensor less solutions**[20]**. Our designed motors need to be Hollow disc for high rpm and high Torque.

- **Factors Considered during Motor Design**
    - Stall and low speed High Torque
    - On-Load high Speed
    - Damping control
    - Position control
    - Efficiency
    - w/ & w/o Cooling
    - Bearing Integration
    - Planetary Gearbox
    - Service life
    - Braking control
    - Spring control.

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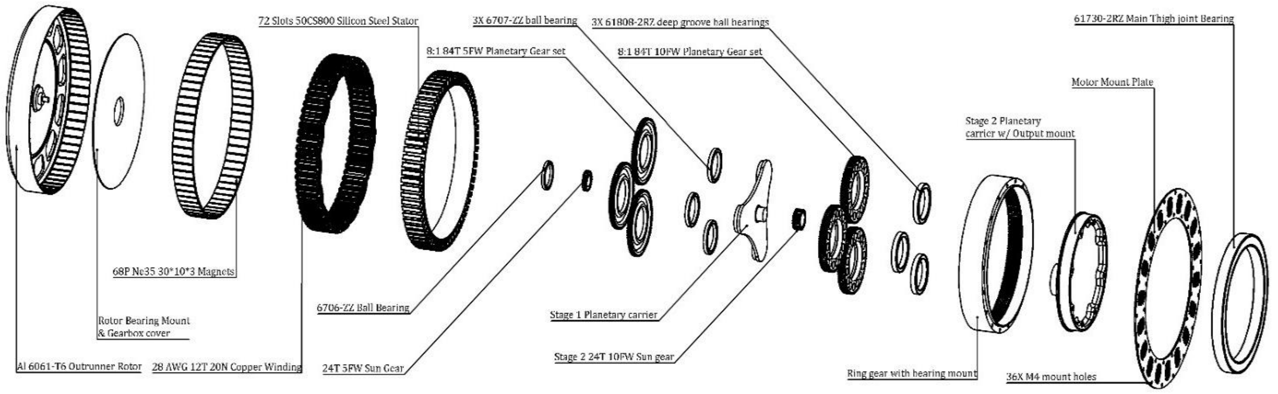

Fig. 23.Motor Design Exploded View

- **Stator:** A 72 Slot Silicon steel (50CS800) Core is used as stator, due to its iron loss of only 4.98W/kg and magnetic flux density 1.55T. 28 AWG motor winding copper is used in windings with 12 Turns of 20 wires in Hand so that it can pass currents upto 350A. This is for 24040 motor, other motors have similar winding Configuration and materials.
- **Rotor:** Outrunner rotor is used because it provides space for planetary gearbox which can be fitted inside the stator. Neodymium N35 magnets are used of various sizes from 8mm to 30mm with common thickness of 3mm. Instead of its weaker Remanence (1220mT) than N52 grade magnets (1480mT), it is used due to availability in various sizes and cost.
- **Gearbox:** It is most important part of our Actuator as it is used to increase torque, but in this exoskeleton to lift 300Kg a huge amount of torque is needed. So each motor has 2 stage planetary gearbox to provide gear ratios upto 72:1. This gearbox is placed right behind the main bearing into the stator's hollow space.

Table- VI:Planetary gearbox Configuration

Motor	Ring-Planet-Sun Teeth	Module – Face Width	Gear ratio (1 Stage)
11040	127-55-17	0.5-6/10	8.5
14540	100-40-20	1-6/8	6
17530	108-45-18	1-4/8	7
24040	192-84-24	1-5/10	8

The materials used for Gears is 40CrMnmo4. 1st stage carrier is made up of EN353 Steel billets. 2nd Stage carrier/Output mount is made of Aluminum 7075-T6.

VII. MOTOR SIMULATION

As main motors are custom designed BLDC for exoskeleton application, it is very important to optimize its parameters by setting different configurations, calculations and materials. Due to unavailability of high torque motors with precision control, these motors are designed and simulated in Altair FluxMotor 2020 software.

Table- VII: Motor performance data

Motor	Rpm/V (Kv)	Torque (N-m)	Load rpm	Current (A)	Power (kW)
11040	170	12.21	7550	89	4.3
14540	150	17.97	5750	118	5.7
17530	90	22.39	3400	147	7.1
24040	120	39.85	6000	353	17

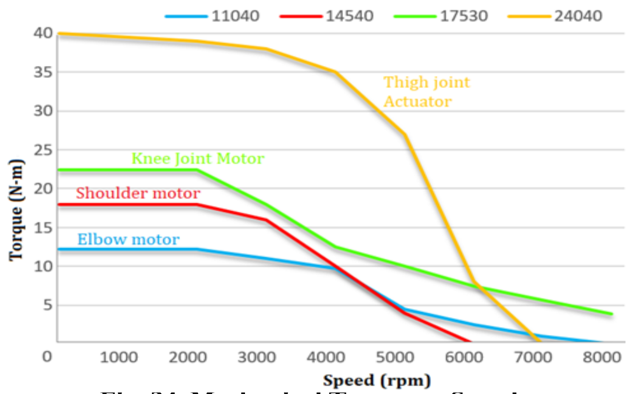

Fig. 24. Mechanical Torque vs Speed

As noticed in above graph Thigh and shoulder motors have significantly high torque at low-medium speeds, but Knee and Elbow motors are designed to outperform at higher speeds insimilar way to human movements.

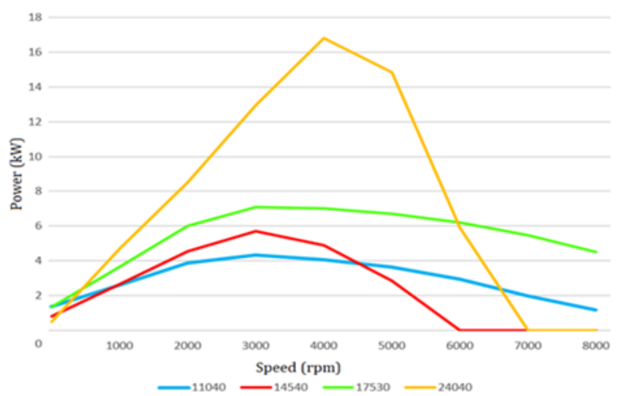

Fig. 25.Apparent Power vs Torque

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This graph has data of 17530 90Kv motor which depicts the operation of motor at torque and speed w.r.t time. Short term operation is considered without cooling for 2-5 seconds and with cooling for 10-18 second. Other motors also boast a similar kind of curves but only difference is of torque and speed data. Motor's non-operating region is also motors working region but it is only used for absorbing shocks, damping and spring action of joints. Very similar characteristics which is observed in human movements.

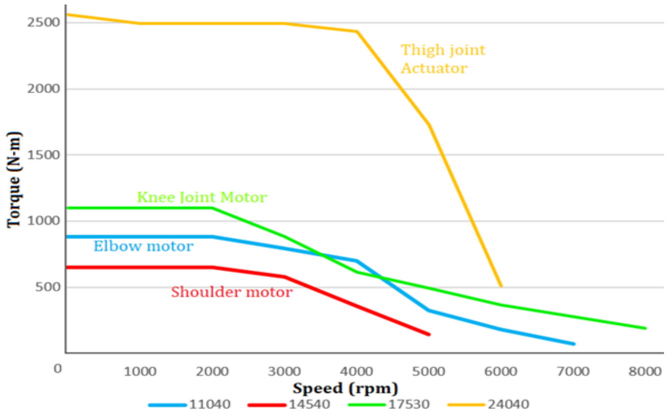

Fig. 26.Torque-speed curves with gearbox

Thigh joint needs very high torque due to its effective distance from ground and also these motors support whole body weight, Hence while lifting an object thigh-hip actuators are under maximum load. Whereas shoulder has motors in 2 axis one of which is front-back movement which has lower torque and other is left-right movement which uses same motor as Elbow joint uses.

Table- VIII: Actuators data with gearbox

Motor	Gear Ratio	Peak torque (N-m)	Cont. torque (N-m)	Speed (rpm)
11040	72:1	879	684	105
14540	36:1	647	540	160
17530	49:1	1097	740	69
24040	64:1	2550	1408	94

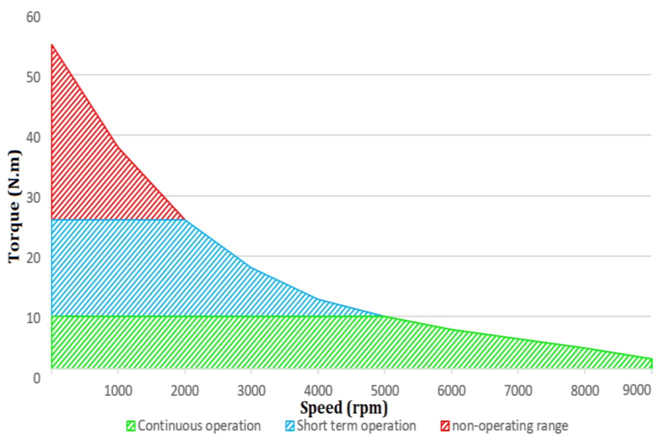

Fig. 27.Analytical graph of motor operation

This graph has data of 17530 90Kv motor which depicts the operation of motor at torque and speed w.r.t time. Short term operation is considered without cooling for 2-5 seconds and with cooling for 10-18 second. Other motors also boast a similar kind of curves but only difference is of torque and speed data. Motor's non-operating region is also motors working region, but it is only used for absorbing shocks, damping and spring action of joints. Remarkably similar characteristics which is observed in human movements.

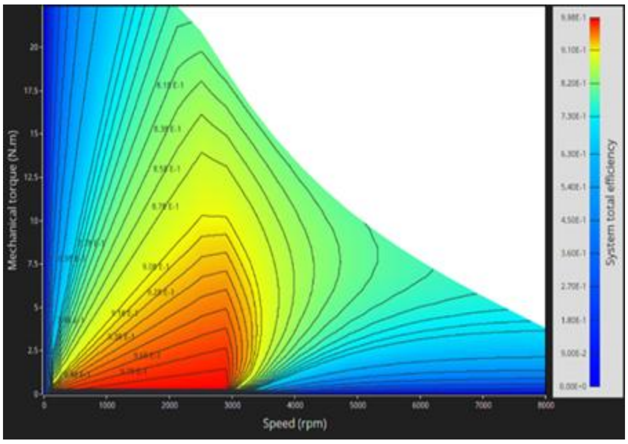

Fig. 28.Efficiency plot on Torque-speed curve

According to simulations, these 17530 motors can operate at 0.98 efficiencies buy at very low torque and low speeds. Carefully analyzing data motors would operate between 0.73-0.88 for most of their loading conditions. During walking without load motors can achieve more than 0.94 efficiencies.

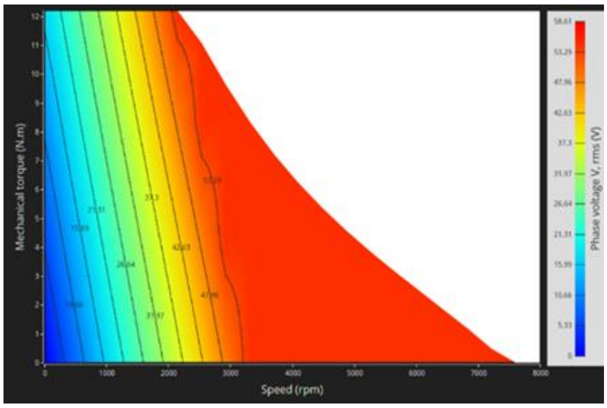

Fig. 29.Phase Voltage plot on Torque-speed curve

This data of 11040 motor shows the voltage required for motors on the torque-speed area. Most of the time motor would be running on 42-55 volts. Similar characteristics are also observed in other motors too.

VIII. CONTROL SYSTEMS

A BLDC motor requires a motor controller to run the motor and hence they are widely used in high-performance machine applications. Generally, they are available for speed control but to be used in robotics speed controllers should work on position control. The major Issue with robotics position control drivers is their Size and weight. This Exoskeleton used speed control drivers which were designed for UAVs and aerospace use. This saves weight and Space.

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Table- IX: Controller Configuration

Motor	Joint	Controller	Control modes
11040	Elbow, Shoulder Y	ODRIVE V3.6	Position, Velocity, Current
14540	Shoulder Z	FSESC6.6	DC, FOC, BLDC (sinusoidal)
17530	Knee	16S 200A VESC	Velocity, current, voltage, power
24040	Thigh-Hip	Custom 400A BESC	Velocity, Current, Voltage.

Table- X: Controller Specification

Controller	No. of Motors	Voltage (V)	Max. current (A)	Cont. current (A)
ODRIVE V3.6	2	12-56	100	60
FSESC 6.6	2	8-60	400	100
16S 200A VESC	1	14-75	300	200
Custom 400A BESC	1	36-150	400	250

- **Custom Controller:**

A simple four-layer design of Controller (refer Fig. 28 & 33), to meet the power requirements of Thigh-Hip joint 24040 motor. As the motor operates on 48V 350A current, there was no other Controller in the market to meet these requirements.

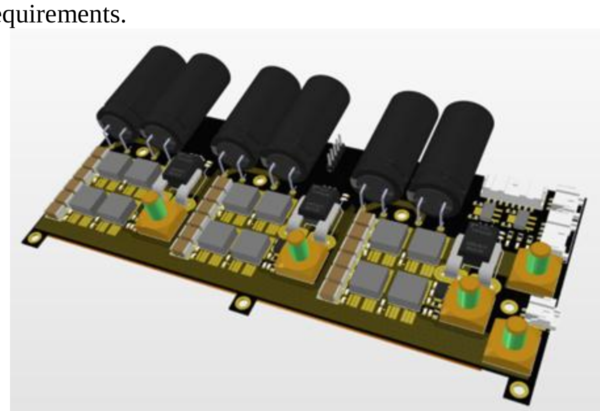

Fig. 30. Custom 400A BESC

- **Main Parts Used:**
  - IPB044N15N5 150V 174A 4.4mR MOSFET
  - UCC27714 600V 4A half-bridge driver
  - ACS758 ±200A hall current sensor
  - WP-SHFU REDCUBE Terminal M6 250A
  - 4.7 uf 200 Vx7r ceramics
  - 560 uf 160V aluminium capacitor

Figure 31:16S 200A VESC

Fig. 32. FSESC 6.63

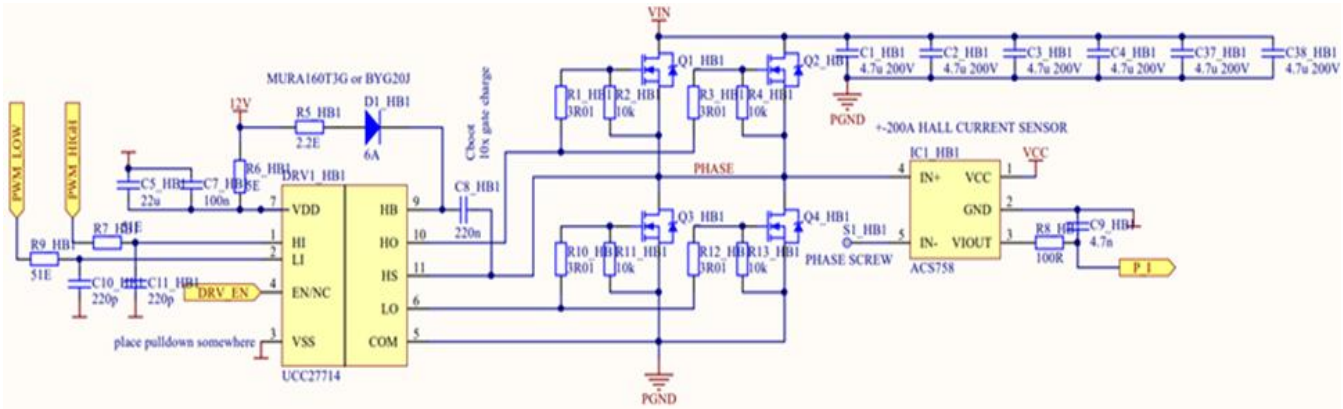

Figure 33:BESC Drive Schematics

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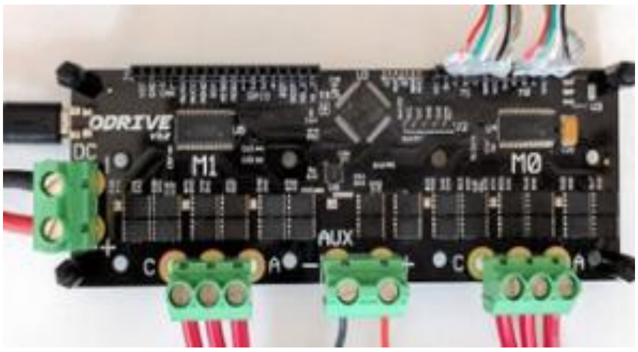

Fig. 34. ODRIVE V3.6

Especially, to perform in position control there are Hall Sensor, rotary encoder, Gyroscope above the rotor to log position of rotor in Arduino motor control unit which uses that data externally to send signals to motor controllers to either increase to decrease speed. It also used PID control for damping, spring modes of actuators. In other driver boards it is done externally but using ODrive controllers it was possible to give precise and fast control to elbow and shoulder actuator.

IX. BATTERY

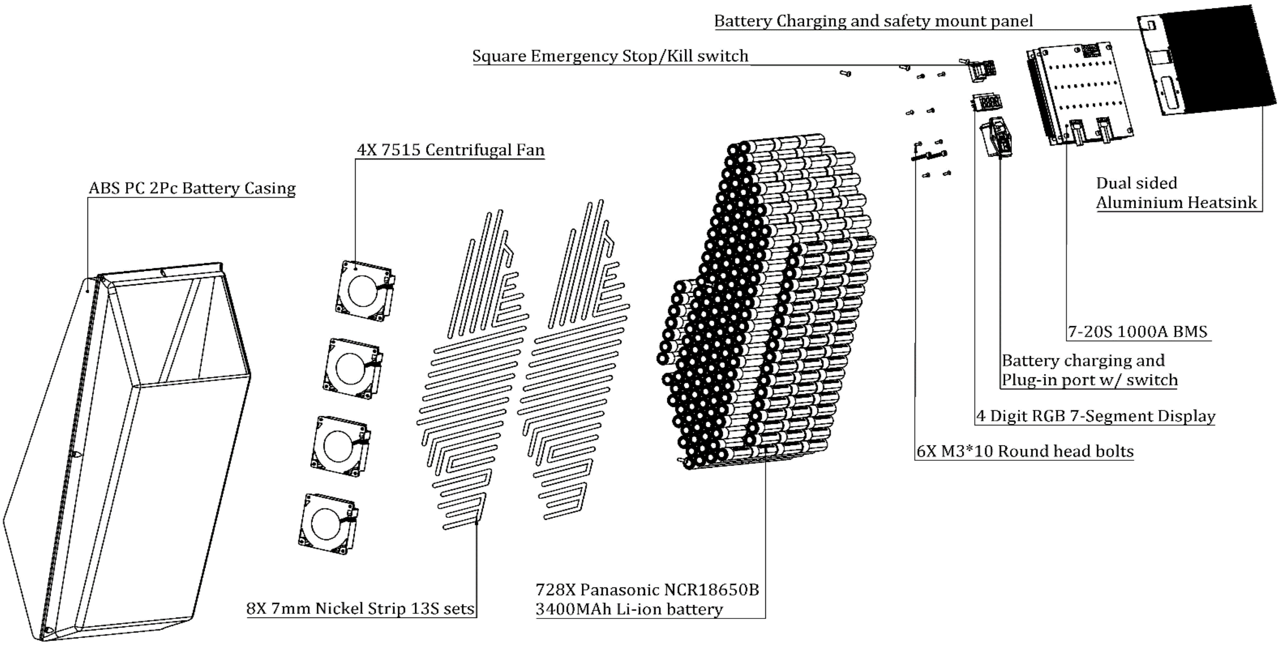

Fig. 35.Battery exploded view drawing

The heaviest component of the exoskeleton is a Lithium-polymer battery weighing 38 Kg. It is designed to last exoskeleton suit for 6 hours of continuous operation. It houses 728 high-performance Lithium-ion cells from Panasonic (Panasonic NCR18650B 3400MAh). The construction of this battery is simple, easily detachable, Water & Dustproof, Plug-In operation makes this bot suitable for manufacturing industries.

Table- XI: 18650 Li-ion cells in market comparison

Battery	Capacity (MAh)	Discharge current (A)	728 cells Weight (Kg)	Cost per cell ($)
SONY VTC6	3000	20	33.92	2.15
SAMSUNG INR1865030Q	3000	15	34.94	2.4
Panasonic NCR18650B	3400	10	33.49	2.45
LG 18650 MH1	3200	10	35.67	2

Calculations:

During holding a weight above the head, the suit resulted in a decrease in muscle activity for the Biceps Brachii (30–70%) and the Trapezius pars transverse (40–70%). This result shows Suit's potential for reducing the physical load on the shoulder and arms for a large range of occupational activities including dynamic lifting and carrying, static work in forwarding bent posture and overhead work**[16]**.

In worst-case scenario, loading exoskeleton suit at 300kg would consume 500A in all motors combined.

No. Cells in parallel = 728/13 = 56 cells.

Total Output Current= No. of cells * Discharge current

Required discharge current = 500/56

= 8.9 A

Meeting these requirements, we found that only a few selected cells can provide higher capacities.

So battery pack configuration is 13S 56P Lithium-ion battery using Panasonic batteries.

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Total battery capacity = 56 P cells * 3.4 Ah
= 190.4 Ah
Total battery voltage = 13 S cells * 3.7 V
= 48.1 V
Voltage when 100 % charged = 54.6 V
Voltage when 20 % charged = 42.9 V
Below 20 % cells start to die and never recharge again. These batteries would last up to 800 Cycles.

➢ **Battery specifications**

- Nominal Voltage: 48V
- Capacity: 190 Ah
- Discharge current: 560A
- Charging current: 100A
- Life cycles: 800+
- Weight: 38 Kg
- Dimensions: 542*300*155 mm

A. BMS

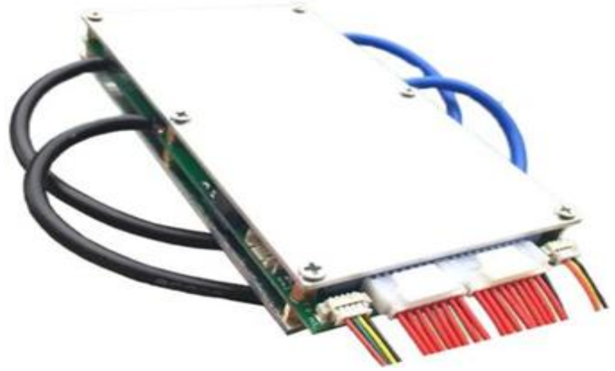

Fig. 36. 7-20S 1000A BMS

This battery uses a BMS which can hold up to 20S and discharge currents up to 1000A. For the Modularity of these robots, several attachments can be loaded on this suit, so the battery management system needs to be of higher discharge current to be able to supply power to attachments like Launchers, Winch, Bucket, jackhammer, Segway, etc.

This is a very standard BMS especially made for small electric Cars, 7-20S 1000A BMS is generic and supports up to 1120 Batteries.

B. Cooling System

As per the current rating of this battery, it is very important to keep the battery cool to prevent cells from leaking and bursting out, which would eventually damage the overall exoskeleton. This exoskeleton uses a common heat sink for Cells and BMS which has 10*1mm fins.

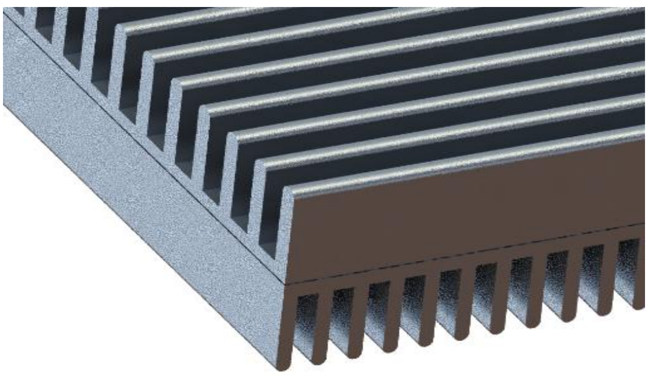

Fig. 37. Aluminum heat sink profile

This battery has 2 layered Aluminium heat sink. The fins are vertical inside the battery and in a horizontal direction outside the battery. Inside the hot air from calls and BMS automatically rises upwards and Cooling fans are used to increase the turbulence and airflow inside the battery. Both heat sinks are connected by thermal paste for better thermal conductivity. 4* 7515 5V Centrifugal fans actively create an airflow inside the battery.

C. Charging and Safety Panel

Fig. 38. Main Battery

This battery has a Control panel at the Back-Top position for easy access. On the Control panel, it has a 220-240V 16A Plug which will be used for charging and Plug-in operation. A 4-Digit 7 Segment display is used to show battery status and capacity. A very important component is Red button Kill switch which is used for safety concerns so that externally this exoskeleton's power supply can be cut off in case of malfunction, fire and emergency.

X. ELECTRONICS

This suit uses control methods ofpHRI signals as control inputs, and the representative methods are force control, master-slave control, and pre-programmed control**[6]**. The Exoskeleton electronics
controller is based on a complex sensor's system which enables to calculation force and pressure applied by the operator, to recognize his intention and properly manipulate the actuators and limbs of the Exoskeleton**[14]**.A strain gauge integrated into each Belt provides the force measurement. Each strained section on the belt as an elastomer to sense strain**[21]**.
A strain gauge on support belts senses the force of human movements inside the skeleton. Using 5 strain gauges on each side provide sufficient data of force in all 6 directions, using vectors the exact direction of force is calculated in the Arduino sensor unit.

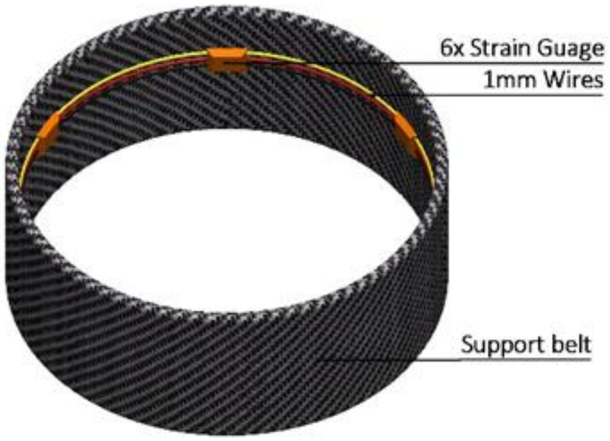

Fig. 39. Strain gauge belt

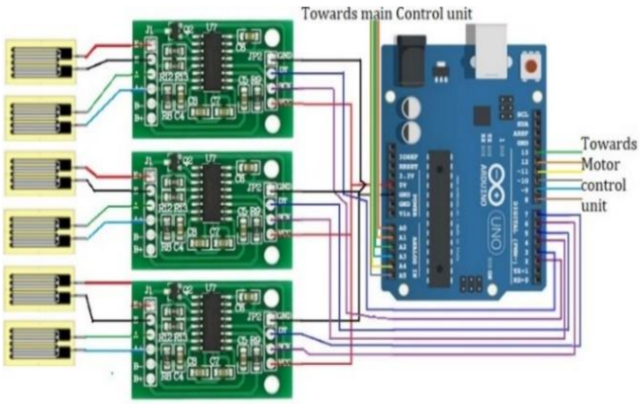

Fig. 40. Arduino sensor unit

There are in total 6 Arduino sensor unit each of them connected to 12 strain gauges and 6 strain gauge amplifier. The resultant force of 6 strain gauges is calculated in Arduino UNO and the final 1 direction, Force, Speed data is sent to the Motor control unit. Also, the Main control unit takes data and matches it with gait cycle curves if the data is within 10% range the motor control unit will work seamlessly, and if not it will immediately send signals to get the correct information and stop exoskeletons functions.

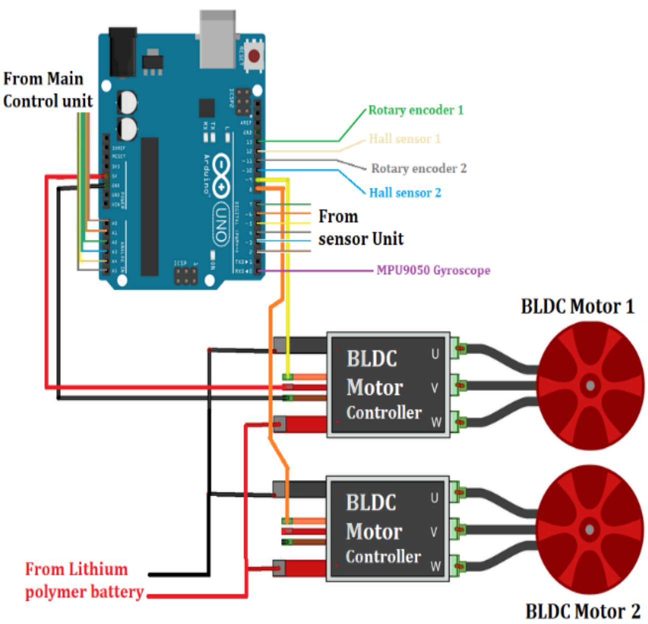

Fig. 41.Arduino Motor control unit

Fig. 41, It is mainly used to get data of linkage position, motor position, motor speed control and the main function of the Motor control unit are to control the motor by position. It is connected to several different sensors and only 2 main motors. Also, it receives data from the Sensor unit and main control unit.

Table- XII: Components in electronics

Component	No's	Location
Arduino mega	1	Main control unit
Arduino UNO	8	The sensor unit, Motor unit
Rotary encoder	10	Motors
Hall sensor	10	Motors
Strain gauge amplifier	33	Thigh and arm assembly
Strain gauge	66	Support belts
Connecting wires	-	Multiple locations
MPU 9050 Gyroscope	9	Every link of the exoskeleton

The Slave controllers measure the joint angle and speed, the force sensors of the lower and upper arm, the force sensors installed in the Velcro belts and abduction-adduction position measurement systems. The high-level control system relies on the controller. The control system calculates the proper value of the supporting torque of each joint and sends these reference values to the joint controllers. Each Controller can control up to three Actuators. Furthermore, the processor communicates with the battery management system (BMS) in Battery. The BMS observes the cells currents, voltages, temperature, calculates the delivered energy and communicates with the main Controller also via the CANOpeninterface**[17]**.

XI. MECHATRONICS INTEGRATION:

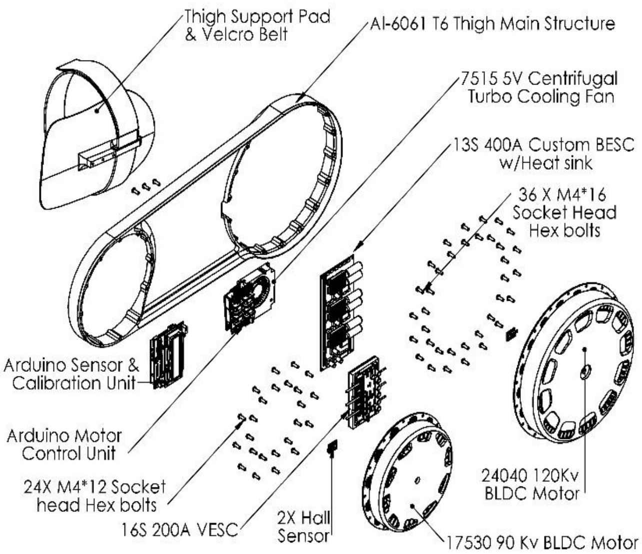

Fig. 42. Exploded isometric view of Thigh link

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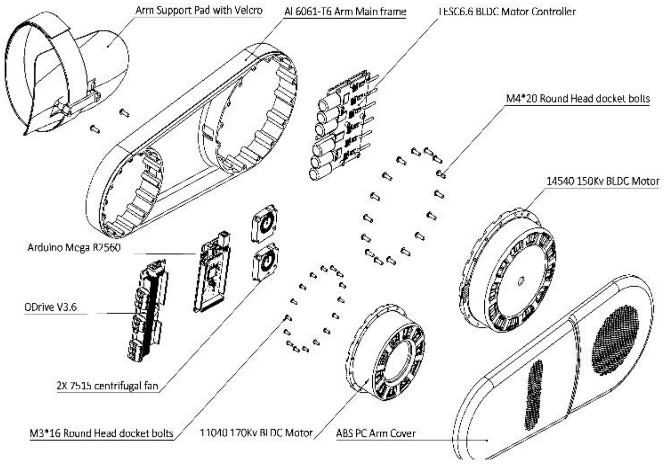

Fig. 43. Exploded isometric view of Arm link

All power electronics components are placed in this for unified cooling of full inner thigh there are many small holes on covers and the 7515 Cooling fan takes care of pumping air inside the thigh. Using this design made it possible to reduce costs, weight, better cooling, easy reparability.

XII. PERFORMANCE SCENARIO:

Requiredtorque :

1.)Static Condition-LifitngScenario :

In static condition lifting an object is performed by bending forward the exoskeleton by the actuation of knee & Hip Joint, in lower body ,Shouldr& elbow joint in upper , the intuited posture is shown below figure:

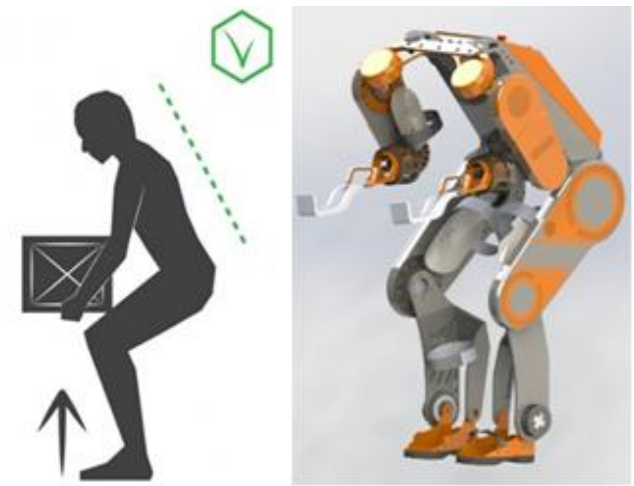

Fig. 44. Lifting posture of exoskeleton with a normal human lifting posture

Here , during the lifting scenario the hip joint will have maximum 40-45 dgree actuation & knee joitn will have 25-35 dgree actuation with respect to vertical . the intuated posture while lifting is shown in above figure

By considering the above posture in cad one can calculate required torque generated in this particular position if we know the CG of each components , its weight & distance of cg with respect to the joint considered .the below tale gives the mass of each components considered:

Table- XIII: Mass of major components and Sub-systems

Component	Mass(Kg)
Main Frame	9
Battery	38
Control systems	2
Cooling systems	0.6
Ergonomic pads	1.1
Bearings	0.7
Actuators	24
Cables & wiring	1
Safety systems	1.5
Miscellaneous	1.1
Total	**79**

Here we are only considering the CG & weight of actuator ,battery & Pay load of 300kg by neglecting other, the mass for specific actuators is given below.

Table- XIV: Mass of actuators

Motor	Joint	Mass(kg)
11040	Elbow, Shoulder Y	1.62kg
14540	Shoulder Z	2.9kg
17530	Knee	3.67kg
24040	Thigh-Hip	6.5 Kg

A) Hip-Joint:

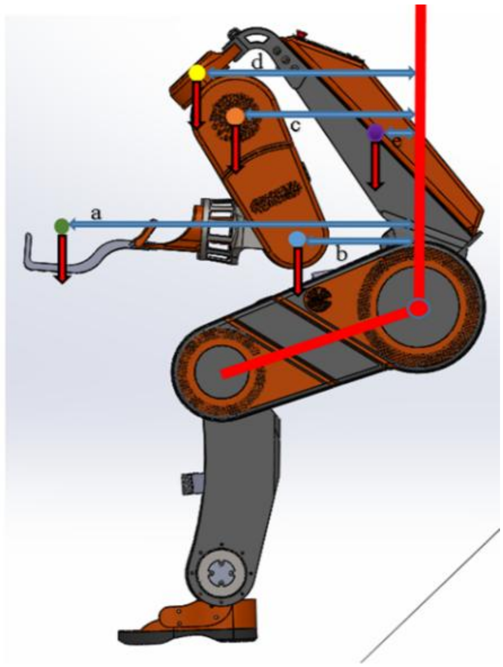

Fig.45 Illustartion of CG points W.r.t Hip joint

Here the exoskeleton components is CG is calculated, with respect to the hip joint, such the perpendicular distance is measured from the vertical red line to CG-points.. the payload considered was intended “300kg”. The total length of the trunk was 54cm, the battery has weight of 38Kg & CG distance was calculated from the CAD model as below:

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Table- XVI: CG OF Components W.r.t Knee-Joint

CG	Colour	Perpendic-ular Distance(m)	Force (N)=Mass x 9.8
Pay-Load	Grey	a = 0.32m	2940N
Elbow Motor	Blue	b = 0.14m	31.752N
ShoulderMotor (z-axis)	Orange	c = 0.02m	56.84N
ShoulderMotor (y-Axis)	Yellow	d = 0.05m	31.752N
Battery	Purple	e = 0.3m	372.4N
Hip Motor	Green	f = 0.33m	127N

Table- XV: CG OF Components W.r.t Hip-Joint

CG	Colour	Perpendicular Distance(m)	Force(N) = mass X 9.8
Pay-Load	Green	a=0.7m	2940N
Elbow-Joint	Blue	b=0.23m	31.752N
Shoulder-Joint-Z	Orange	c=0.36m	56.84N
Shoulder-Joint-Y	Yellow	d=0.42m	31.752N
Battery	Purple	e=0.08m	372.4N

From the above study & data acquired we can calculated Torque developed due to the weight Pay-load & actuators:

$$\tau = \underset{r}{\rightarrow} \times \underset{F}{\rightarrow}$$

$$\text{Total } \tau = [a \times F_1(payload)] + [b \times F_2(Elbow)] + [c \times F_3(Shoulder - z)] + [d \times F_4(Shoulder - y)] + [e \times F_5(Battery)]$$

=2058 + 7.3 +20.52 + 12.06 +30 = **2129Nm**

So, 2129Nm is the torque required while lifting a load of 300Kg, as 2129 is the total load, considering the loaded is divide in both leg on one individual leg the torque required will be 2129÷2=1065Nm in anti-clockwise direction

B) Knee-Joint:

In Similar manner to the hip joint the torque developed at the knee joint was also calculated, here for thigh joint with respect to the cad model dimension

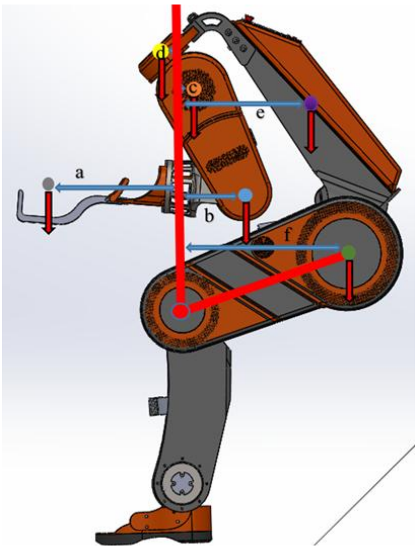

Fig.46. Illustartion of CG points W.r.t Knee joint

Similarly as before,total torque required is:

$$\tau = [a \times F_1(payload)] - [b \times F_2(Elbow)] - [c \times F_3(Shoulder - z)] + [d \times F_4(Shoulder - y)] - [e \times F_5(Battery)] - [f \times F_6(Hip)]$$

= 941 + (-) 4.4 + (-) 1.13 + 1.6 + (-) 111.7 + (-) 13.44 = **812Nm**

Here, the torque is positive which means it is in anti-clockwise direction, the torque required was 812Nm, so for individual leg it will be 812 ÷2=406 Nm at each leg. 300 kg pay-load

2.)LocomotionCondition :

This condition can be evaluvated with the torque analysis Performed in Ansys-workbench , by the integration of normal gait values acquired from opensim simulation,
*Note:*the torque analysis in ansys was done by considering the payload as 300Kg & weight of exoskeleton as 60 , but here the exoskeleton weight is 79 , which is excess of 19 kg , which we can reduce from payload, so in actuall practice the exoskeleton can only carry 300 -19 = 281Kg of payload for the acquired normal reaction acquired through ansys
The below Table Compares the torque Required in the above two conditions with the actual-torque available or generated by actuators

Table – XVII : Required Torque Vs generated Torque condition

Condition	Joint	Required Torque(Nm) per joint	Generated Torque-cont. (Nm) per joint
Static-Lifitng	Hip	1065Nm	1408Nm
	Knee	406Nm	744Nm
Continuous-Locomotion	Hip	1378Nm	1408Nm
	Knee	808Nm	744Nm

It can be found from above analysis that while lifting the payload of 281 Kg& considering weight of exoskeleton as 79 kg as both the joints of Hip & Knee in each leg is working together the required torque is less is within the torque generated by exoskeleton , But in continuous locomotion we can see that Hip joint is well within out limits but for knee joint. that the required torque is more than the generated torque by the motor by a 8%, which implies that our designed actuator can only work under the 8% decreased payload of total 281Kg : which is:
[300-[[300×8]÷100]=**258Kg**.,
This ,is the max payload that the exoskeleton can operate

Maximum speed:
=Actuator on-load (rps) * ground to thigh height * No. of legs * Step arc length
=0.9 * 0.84 * 2 * 0.9
=1.36 m/s = 4.896 Kph

Battery life:
Considering the continuous operation of the suit with 80 kg for 45 minutes in 1 hour

Current consumed by all 1 side on motors in suit=

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Peak current*continuous current factor
=(89+118+147+353)*0.1=70.7 A
For every one-hour suit
will consume 53.02 Ah
Overall battery capacity is 190 MAh
On average 190/53.02
= 3.6 Hours.
The battery can last more depending on the speed of work and weight

XIII. RESULTS AND CONCLUSION

Thispaper introduces a the idea of developing a Full body exoskeleton suit prototype which is intented to be used for heavy duty application in Manufacturing sectors , Defence sectors & some civilian sectors .the design was fully mobile type & is not restricted to any particular space. the design was able to be validated in both static condition. static validation was done by manual computation & software compuatation “Ansys workbench” .Although Static structutral analysis was done the dynamic analysis was not performed due the limitation in hardware & Software tools , here dynamic analysis can be done in future which will further give us the result with more precision,here the end effector design was a simple “hook type”which is convenient for most of the uses ,but can be changed depending upon the payload characterstics

The user-actuator control was by the use of strainguage belts which was used around the limbs for the detection of signal for actuation . The gait Assist function Introduced in the prototype helps us in reducing actuation lag , this function also can be used as a reference limit for drive controll at which the device is actuated. The gait analysis was performed using an existing Opensimmodel , here further study & analysis of the gait cycle can be done for different conditions like in slope terrain ,steep terrain , rough terrain etc..from which the data could be used for gait assit function or for other computational needs.

The prototype was aimed to have a top speed of approximately 3 – 3.5m/s , the structural was designed to be able to survive the payload while locomoting under 3-3.5m/s , but due to actuators restrictedactuation speed the max speed is only around 1.36m/s . this is a the weight of the suit was expected to be under 60kg ,this was not able achieve ,the final weight is 79kg , the main components that contributed to increase in weight was actuator & battery. Battery capacity should be more inorder to be able to work continuously and at least 5% more power electronics systems would increase suits continuous performance.In future this drawback of actuators restricted power due to efficiency& weight of battery can be decreased , by further research for making the design more compact &ideal .

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